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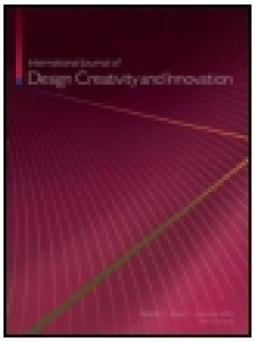

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ARTICLE

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ABSTRACT

The present paper illustrates a pilot experiment in which a new model for fostering creativity in the product development process is tested with novice engineers. After introducing creativity in the field of product development, the current author presents the new standard. The theoretical background that embodies the new model is presented, based on relevant literature. Making use of the new model, a methodology for testing it, using novice engineers is then proposed. It relies on the comparison between novices that were trained in the model in comparison to other novices that were not trained in the model. Higher results for creativity achieved by novice engineers that have employed the model show the advantages of its application during product development activities.

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KEYWORDS
Creativity; engineering design; product development

1. Introduction

Engineering design, along with product development (PD) is a creative process, and both rely on interdisciplinary thinking (Pahl et al., 2007). Creative cognition is one of the props of interdisciplinary thinking (Fink, Ward and Smith 1999) and in engineering design activities, creativity in PD is an issue of great significance for companies nowadays. In a very competitive world, where engineering design skills are mandatory, the capacity to be creative is based on the essence of creative thought, and therefore creativity cannot be reduced to a set of rules of thumb. The basic principles that drive creative thinking must be clearly understood and established so that an improved framework for designing innovative products and services can be materialized. In fact, PD is a dynamic process and is nowadays characterized by restricted time limits, significant design assessments, and gates to decision-making (Cooper, 2005; Ulrich & Eppinger, 2003). Most of the companies are under stress to bring new products to market as soon as possible, and in many areas, they must work firmly to deal with increasingly more complex customer needs. The aim is to generate valuable results on a constant basis, enhancing a creative problem-solving attitude, and provide more decision-making authority to project leaders (Smith, 2007). In this information-based approach, the development team produces a constant flow of purposeful work and high-quality information (contributing for risk reduction) for dynamic and real-time decision-making. Within this, a more active and flexible PD organization is established as opposed to traditional rigid structures based on Cooper's stage-gate frameworks (Cooper, 2005). Creativity is a fundamental building block (De Graff & Lawrence, 2002) for the development of innovative products. A new

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model of creativity that processes information more effectively suggesting how an engineer may foster creativity within his team, staying within the engineering requirements, budgets and the time schedules imposed must be prescribed. As so the main objective of this paper is to understand how creative ideas are generated and how they can be brought to the PDP (PD process), thus defining a new model for fostering creativity which lead to the following research question:

Does the mere exposition and training of the model to group(s) of people allow them to achieve better creativity rates in a new product design output (i.e., prototypes) than group(s) that were not exposed and trained in the model?

For testing the model, a methodology using novice engineers is proposed as an initial pilot case study. Finally, some distilled lessons are drawn at the end of the paper.

2. Materials and Methods

This section presents a brief literature review of the main concepts that are important to be taken into consideration from a dual engineering-cognitive perspective to present the model. The first subsection (2.1) defines creativity, then the next subsection (2.2) gives a short-term introduction to the cognitive essence of design and PDP. In section 2.3, the main components of the model are outlined.

2.1. *Defining creativity*

Several definitions of creativity can be found in the literature (e.g., Amabile 1996, Csikszentmihalyi 1999; Weisberg, 2006). In a simple definition, creativity is the ability to produce work that is both novel and appropriate (Sternberg & Lubart, 1999). Creativity is considered by most researchers as a topic of relevant importance at both the individual and public stages. For the individual, creativity is normally used for problem-solving and for the society it can lead, for example, to inventions, new scientific discoveries, and movements in art (Csikszentmihalyi 1999). Creativity in product innovation is the ability to conceive novel products that, after having gone through the development process (Ulrich & Eppinger, 2003), will be introduced in the market and/or patented. Creativity and innovation are not quite the same thing and are distinguished in the field of psychology (Amabile 1996). In the case of an enterprise or an organization, the term innovation is more frequently used, instead of the term creativity, to refer to the entire process by which new ideas are created and converted into original, useful and viable products, new processes, innovative marketing activities, important organizational changes, and business practices, ultimately based on research and development activities (Kelley & Littman, 2004).

Within creativity's discussion, the concept of 'surprise' has been gaining importance as a driver of unexpectedness (Becattini, Borgianni and 2017, Macedo & Cardoso, 2001). The work of Becattini, Borgianni and Cascini (2017) reflects about the role of surprise in the creation of new products, evaluating it as a nuance of originality, an autonomous dimension, or an emotive response to new products. Furthermore, creativity encompasses activities that allow people to produce creative products and can depend on motivation and personality traits (Amabile 1996). Besides to a product being novel it should also have value to the society; in the sense to decide if the product is 'creative' or not (Sternberg & Lubart, 1999). Csikszentmihalyi (1999) presented an analysis of the concepts of novelty and value in discussing creativity. According to Csikszentmihalyi (1999), creativity should be seen from the point of view of three important components: 1) the individual, who makes a novel variation in a domain; 2) a domain, consisting in a set of practices and rules; and 3) a field, consisting of experts from a social organization of a domain. The author sustains that creativity should be used to describe a product that passes through these three components.

Amabile (1996) characterized the task to achieve product innovation as being heuristic rather than algorithmic. Amabile (1996) relies on personal skills that are relevant to the domain in which an individual is working, including his/her knowledge and technical abilities. Skills are based in natural abilities and acquire during formal and informal education and training. They also rely on 'creativity-relevant skills' such as the case of heuristics. The author typically defined an algorithmic task when the path to the solution is straightforward; on the contrary, a heuristic task is when it does not have a clear path solution and for which algorithms must be developed. Sternberg (1999) proposed that a crucial aspect of an innovative product relies on the effect that the product has on the experts of the field. A creative product can change the direction of it. Sternberg (1999) presented eight different kinds of creative contributions affecting the direction of a field. In fact, creative ideas and products are normally involved in discussion in deciding what is creative or not. Despite that, the systems through which an innovation occurs can be quite normal according to Newell and Simon (1972) and as cited in Weisberg (2006). This fundamental aspect is based on the essence of design – creative cognition – as Boden (1992) denoted.

More than simply finding definitions for creativity, one objective is to bridge the gap between creativity and engineering design, as earlier proposed by Ferguson (1996, p. 56), when the author advocates that creativity in engineering design is 'intended to describe the ability of some minds to synthesize new ideas from a combination of past and present experience or from elements experienced separately.' For the case study in cause, judges will have their own definition of creativity in judging the outputs.

2.2. A cognitive approach to the study

Cognitive psychology is concerned with the study of mental processes such as perception, language, memory, problem-solving, and decision-making, among others especially with respect to the internal events occurring between sensory stimulation and the clear expression of behavior (Thagard, 2005). Cognitive psychology is on the one hand, an important subject within the scope of this article and proposed model, and on the other hand, an essential science for the comprehension of an individual's mind that belongs to a design team. The focus of discussion is centered in the subjects of problem-solving and decision-making, concepts typically studied in engineering design problems (Cross, 2001). Other subjects such as memory, language and perception are to be discussed elsewhere (for example, Goldstein 2008).

The use of knowledge in problem-solving is a 'top-down' process. This is, driven by the necessity to accomplish a goal. Top-down processing is based on the flow of information from the top of the system to the bottom of it (Weisberg, 2006). A top-down approach (also known 'step by step design' and 'decomposition,' respectively) is essentially the fragmentation of a system to promote understanding of the composition of its subsystems. In a top-down approach, an overview of the system is formulated, starting from a final instance to the initial one. Each level will be detailed, from the highest to the lowest, to arrive at the specifications of the most basic levels of the element covered (Wolfe et al., 2003). 'Bottom-up' is the opposite or complementary process. In a bottom-up approach, the basic elements are initially described in detail. These elements are associated to form a larger subsystem, which can then be associated with other elements at many other levels eventually until completing the highest level of the objective system. Bottom–up and top–down processing of information and knowledge are often studied in the domain of cognitive psychology (Goldstein 2008). Another example of these situation occurs in the field of artificial intelligence and computer science, where bottom–up is used as a synonym of functional synthesis (composition or construction) and top–down of functional analysis (decomposition) (Lawler & Yazdani, 1991). Knowledge is used to direct all the activities in the environment, including thinking ones. Cognitive researchers found evidence for the important role played by knowledge in processes of storage and retrieval of information from memory, in forming images, in problem-solving, and so on. Besides, knowledge and experience are expected to be of crucial importance in problem-solving and the conception of new things (Weisberg, 2006). The model to be presented further on will incorporate those above aspects in the main processes that compose it – they will be named as: 1) decomposition and 2) integration.

Also, the 'modern' research on problem-solving is based on the 'information-processing approach' proposed by Newell and Simon (1972) and cited by Simon (1999), in which individuals are compared to computer programs to carry out problem-solving. In this approach, Simon (1999) considers an initial situation or problem state (conditions at the beginning) and a goal state (the solution of the problem). Intermediate states are normally achieved between the start and the solution of the problem and are called *problem spaces*. A concept that will be take into consideration to describe the main two processes introduced just before this paragraph.

As recognized, in problem-solving both 'well-defined' and "ill-defined problems are considered, and consequent problem spaces (Cross, 2001). A problem with all the components specified is called a well-defined problem (Simon 1999, Weisberg, 2006). Conversely, in ill-defined problems, at least one of the components is not specified in the statement of the problem. Engineering design problems show an ill-defined characteristic, and it is frequently not clear at all what the problem is (Cross, 2001). In the case of well-defined problems, the task is to find a sequence of moves that leads from the problem to the goal. Many problems have problem spaces that are too large for an individual to search within it. When faced with a problem space that is too large to be searched, heuristics are used to simplify all problem space. That is so important why heuristics are used in design and PDP.

The tenure of certain knowledge can be used for problem-solving (Weisberg, 2006). According to Weisberg (2006), two important different uses of knowledge during problem-solving are observed: analogical transfer (or analogy, as some authors call it; for example, Welling, 2007) and expertise. Analogical transfer occurs when an individual solves a problem by transferring information (normally in the form of knowledge) from a previously solved problem to deal with a new one and having the similar structure of the known one. This is a recognized type of problem-solving allowing creative thinking to occur (Weisberg, 2006). Analogies are used by all individuals in their daily activities to comprehend and imagine about new concepts as well as to explain problems. In a study performed by Linsey et al. (2008), design by analogy was an important part of the design process across the different of modalities used by designers such as sketches and diagrams. The article presented an experiment that explored the effects of retrieval and the use of analogies in it. The authors found that the level of abstraction for the representation of previous knowledge affects individual's ability to retrieve and use analogies for problem-solving (Linsey et al., 2008). Hence, the use of analogy is the first important heuristic to consider in the new model.

Regarding practices on decision-making and at a more conceptual level, fast and frugal heuristics can be used (Magee & Frey, 2006). Fast and frugal heuristics are strategies to decide quickly based on limited information and very little computation. Although something can be lost when using these heuristics their extreme speed and economy of resources may provide advantages in situations where a decision must be made in a limited timeframe and other more powerful decision methods are useless. In other situations of product design processes, where concepts may be more developed at a certain phase of the process, the Pugh controlled convergence methods can be used (Frey et al., 2009). The Pugh controlled convergence methods consist of pair wise comparison of ideas using a set of criteria to converge on the best idea of the set.

Other attempts to understand and promote creative thinking in design can be used (Cross, 1997). An example is association thinking (for example, brainstorming). 'Descriptive models of creative thinking' have also been developed through research in artificial intelligence (Rosenman & Gero, 1993) as cited in Cross (1997). The authors suggested 'four procedures' by which creative design might occur: combination, mutation, analogy (just described) and 'first principles'. Combination will be also described by Welling (2007) in the next subsection. Mutation involves changing the form or the shape of some attribute or attributes of an existing design (Cross, 1997). First principles are a way of generating creative designs. This causes difficulties in identifying what 'first principles' are in design and how they may be used to create design concepts. An example was given by Rosenman and Gero (1993) and as cited in (Cross, 1997) in the conception of the original 'balance' chair from the first principles of the ergonomics of sitting posture.

Expertise is another use of knowledge for problem-solving and studies in different domains show that expertise can facilitate problem-solving (Ericsson 1999, Cross, 2001; Weisberg, 2006). Experts are individuals characterized by carrying a profound knowledge (and experience) in the domain that is relevant to the problem to be considered (Weisberg, 2006). These individuals have devoted a great deal of time (normally more than 10 years) within a certain subject. This '10-year rule' (Chase and Simon 1973) cited by Ericsson (1999) has been found to comprise many domains including some that involve creative work such as product development. Experts and novices are common groups used in PD tasks for assessing important distinct characteristics of them. To set the model novices will be tested.

2.3. Related work

In the present subsection, some theories and ideas that are the backbone of the model are introduced. Some of the concepts in the present model are not unique and other authors may be used, as for example, in the case of heuristics. Regarding those items, some important work has been also developed by e.g., Belski (2009), Yilmaz et al. (2010), Saliminamin et al. (2019). In this case, the paper focus on the heuristics selected to present the model to the students (novices) and proposed by Goldenberg and Mazursky (2002). Of course, all the others can be used with the same purpose.

2.3.1. The art of though and creative mechanisms

The work of Wallas (1926) proposed a pioneered process model to explain how individuals work through creative problems, suggesting four stages, including 1) preparation, 2) incubation, 3) illumination, and 4) verification. Although the model possesses unique features, the general remark remains on the idea that creative problem solving requires on several generations and evaluating potential outcomes to complex problems. In fact, this idea should be in the essence of creative though. Also, in reviewing some theories of creativity, Welling has encountered four mental mechanisms that are important for creative cognition (Welling, 2007). The first one is the 'application of existing knowledge'. This is a kind of mental mechanism that consists of the creative replication (Sternberg, 1999) of existing conceptual structures to match normally occurring variation. Application of existing knowledge is understanding the framework that the designers are working within. This could also be that engineering students must be aware of physics, mechanics, and fluid flow to design a system. 'Analogy' is the second mental operation (Welling, 2007). Basically, it implies the transposition of a theoretical structure from one usual circumstance to another one, where the theoretical association among the parts of one state is analogous to the one established in the new frame. Applying engineering concepts from one circumstance to another is a good example of creativity through analogy. 'Generation of combinations' (Welling, 2007) is the third mechanism, viewed as the merging of two or more concepts into a new idea. In the field of engineering, combination plays an important role, as far as many creative technical solutions are the result of bringing together existing elements in a new, useful, and practical manner. The last creative mechanism is 'abstraction' (Welling, 2007). The mental process of abstraction may be described as the result of generalization by reducing the information content of a structure, regularity, or pattern that is present in several different physical or mental perceptions. The all four mechanisms can be viewed as having specialization characteristics.

2.3.2. Inspirational sources

Although creative cognition can be explained by mental mechanisms mentioned by Welling, they should not be considered apart from the conditions under which the ideas arise. The following paragraph introduces the way creators find inspiration for their new ideas. Stefik and Stefik (2004) classify the sources of inspiration in four main categories: 'theory-driven,' 'data-driven,' 'method-driven,' and 'need-driven.' In the theory-driven approach, a mind model or hypothesis provides a way of thinking that guides to insight and invention. In the data-driven approach, an irregularity in data discloses new possibilities Stefik and Stefik (2004). A creator notices that something surprising appears in the data, leading to insights and invention. In the method-driven approach, instrumentation enables formerly unknown situations. Researchers have a new instrument that allows them to examine things not previously seen giving them advantages in observation, leading to insights and invention Stefik and Stefik (2004). The need-driven approach identifies problems and look for new solutions. A creator realizes about an unresolved need or problem in the world and hunts for an approach to fulfill it or resolve it. This approach fosters invention as the dilemma rests at the back of the psyche as an unresolved confront. Theory, data and method driven sources set off curiosity and inspire the process of knowledge creation while the need driven approach emphasizes the purpose and usefulness of the invention: in a PDP context, creativity can be triggered by inspiration sources.

2.3.3. Heuristics

Goldenberg and Mazursky (2002) proposed a set of heuristics that can be used for developing the creativity process in PD. Goldenberg and Mazursky sustain that the evolutionary process of successful products present certain regularities that are impartially verifiable and consistent for generally any kind of product. The analyzes of the evolution of mature products (stepping back in time) results in the identification of certain regularities materialized in 'creativity templates', that are a set of experience-based rules, that can be used as an aid to solve new design problems, reducing the risk of new processes. Five 'creativity templates' or heuristics are identified: 'attribute dependency,' 'replacement template,' 'displacement template,' 'component control,' and 'division' (Table 1). Goldenberg and Mazursky tend to think that ideas come from two sources of inspiration: an intrinsic source based on creative thinking, called 'new', and an extrinsic source based on market data. Heuristics are essential tools used in problem-solving.

2.3.4. Domain dynamics

Sternberg (1999) proposed a propulsion model that characterizes seven different kinds of creative contributions in a domain. The seven types of creative contributions are split into two categories: creative contributions that accept current domain paradigms and creative contributions that reject the current paradigms. So, in principle a domain evolves through specialization, using the same paradigm, and/or through generalization, by changing the current paradigm of a domain. The idea behind specialization and generalization is confirmed by Ware (2008). According Ware, the human brain operates as a set of 'nested loops' when dealing with problem solving – generalization loops process generalities and evaluates the global problem (potentially triggering a paradigm shift), while

Table 1. Heuristics and definitions (adapted from Goldenberg & Mazursky, 2002).

Heuristic	Definition
Attribute dependency	Finding two self-governing variables (a change in one does not cause a change in the other) and creating a new relation between them.
Replacement	The replacement of a component existing in the system or in its instant surroundings to accomplish an essential function.
Displacement	The exclusion of a fundamental component from the design including its function, in a way that causes a qualitative modification in the design
Component control	Making a new relationship between a component in the internal setting of the product and a component in its external environment
Division	A certain component is tearing into two, and each new component becomes accountable for a different function

specialization loops manage the details (keeping up the paradigm). Ogle (2007) confirmed this point of view and has gone further, developing an interesting theory for understanding paradigm shifts, breakthrough creativity, and the new science of ideas. Basically, the author sustains that since ancient times, people have believed that breakthrough ideas come from the brains of geniuses. Lately, however, the paradigm has begun to shift to the notion that the basis of creativity lies out there in the network of connections between people and ideas leading to the generation of new ideas. The input resides in what the author calls 'idea-spaces'. The idea-space is based on the use of four inherent characteristics of the individual: insight, intelligence, intuition, and imagination. The output of this change in the paradigm is characterized by dynamism, holism, and self-organizing systems (Ogle, 2007).

2.4. The new model

Having reviewed some thoughts in the field of cognitive psychology and PD, it is observed that they do not completely explain the creative process and lack in some cases full experimental validation of results. In contrast, the model to be introduced below represents for one side the cognitive behavior of the humankind, such as the evidence of specialization and generalization loops in the human mind, and on the other hand is suitable for any situation that requires novelty. The model, illustrated in Figure 1 (where arrows represent the flow of abstract information, boxes the processes, and circles the idea-spaces) holds 'inspiration' and two processes: decomposition, and integration. The environment is an inspiration source needed for designing new products. Inspiration is driven by scientific discoveries, technology achievements, and opportunities from business and market surroundings. While technological and scientific backgrounds will act as a technology push for the development of new ideas and products, the development process is pulled by market needs, hence market pull.

The idea-space changes with the information gathered initially at the decomposition stage and are converted into an extended idea-space. The idea-space(s) is based on the use of four inherent characteristics of the individual (Ogle, 2007): insight, intelligence, intuition, and imagination, characterized by a set of nodes in a network of people that join together and take on an individual set of characteristics, leading to the generation of new ideas. The extended idea-space is composed by four initial product-based items (Goldenberg & Mazursky, 2002; Pahl et al., 2007), which can be

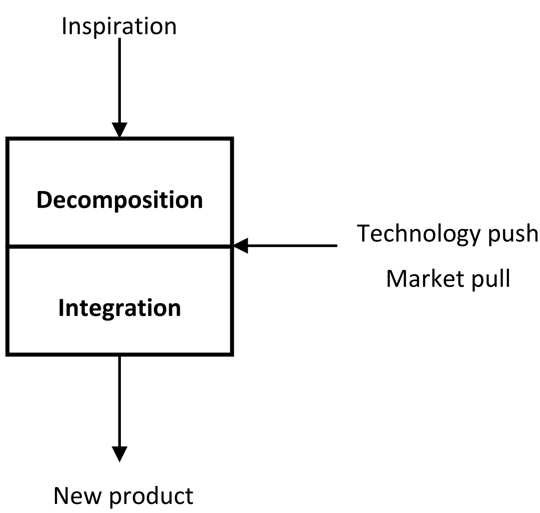

Figure 1. The simplified model.

viewed, in a typical PDP, as understanding and identifying customer needs and consequently setting specifications for achieving customer satisfaction. This can be understood as for e.g., functions and/or components of the product, and/or systems (architecture), and working principles (WP). It is extended once the initial information is converted into a new and enlarged idea-space with no limits for the creation of new concepts based on important product-based items. The 'decomposition' process relies on the concept of idea-spaces (represented in circles in Figs. 2 and 3.), a space of ideas within the domain or problem-space. The first step is to clearly identify the customer needs that will build the initial idea-space, defining initial constraints to the possible solutions provided by inspiration. At the same time, the act of observation and brainstorming (Kelley and Littman 2007) will act on its construction. The decomposition process is basically built on the tilling of all thoughts into lower levels of abstraction to simplify the problem-space. In the case of a complex problem, the hierarchical decomposition helps the mind to structure the problem more easily, allowing a better response based on elementary ideas (top down approach). The decomposition can be better understood as functions, requirements, or customer needs that the product is expected to fulfill in the subsequent integration process. The decomposition process is quite important because it separates the problem from its material aspects feeding and transforming the extended idea-space into material aspects – the former four specific-based items (see Figure 2 for a schematic view).

The integration process analyses, generates, and evaluates the previous information, thus allowing the individual(s) to establish an extended idea-space, used for creating a new product. The integration process is iterative that encompasses two feedback loops: the specialization loop – typical of incremental products – and the generalization loop – typical of breakthrough products (Marques et al., 2014). The first loop develops theories and experiments based on the same paradigm, being subjected, e.g., to the creative mechanisms (application, analogy, combination, and abstraction). The feedback is driven by the degree of match between the theory and the experiment in the testing phase, where the goal is to decrease incoherencies. On the other hand, the second loop generates a new flow of theories and experiments based on a new paradigm presented to the extended idea-space. During integration two situations can happen in the final testing phase just before the final product solution, either the current paradigm is accepted, or it

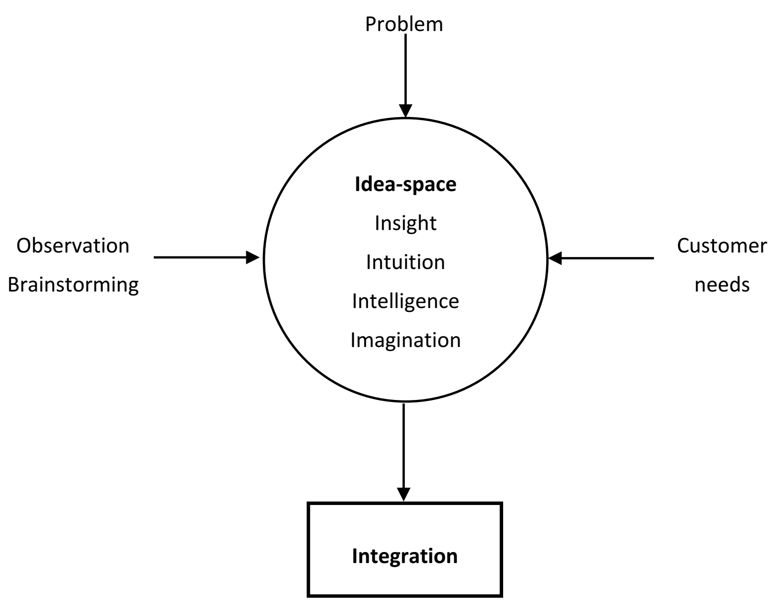

Figure 2. The decomposition process of the model.

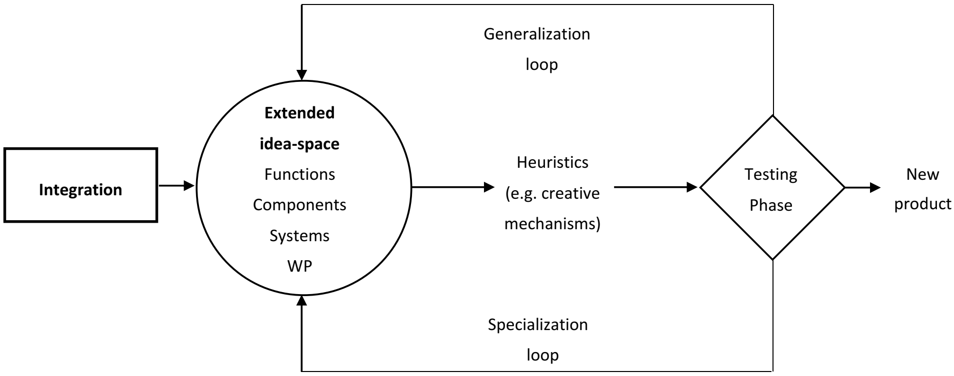

Figure 3. The integration process of the model.

leads to a paradigm shift. The feedback is driven by the level of saturation in the testing phase, where the goal is to get to a satisfactory solution and thus enabling to achieve better creative outputs; if for instance, it becomes blocked at the specialization level. This feedback drives creativity in other directions by presenting a new paradigm to the extended idea-space (changing the product-based), using heuristics, and/or mental discovery (Figure 3). It should be referred that the heuristics can also be used in the specialization feedback in the case of the same existent paradigm.

Special attention to the gates that guide the specialization and generalization loops is quite relevant for possible implications of the new model in product architecture as already suggested (Marques et al. 2018). There is a need to identify a possible saturation in the specialization loop, denoting that there are no other improvements on the design, without changing the extended idea space, or changing the architecture of the product. In terms of product language, this means improvements and optimizations preserving a product architecture that is, achieving a better product within the same extended idea-space. Theoretically, when the potential for improvement is saturated, innovation on the product needs breakthrough, which means novel approaches, requiring a paradigm shift and/or the replacement of items in the extended idea-space. More precisely, the generalization loop could be a change of an extended idea space but is also a change between different product architectures (Marques et al. 2018). New products tend to have an integral architecture; however, with the short-lived and the improved maturity of the product family, their architecture becomes more modular over time, reducing cost and increasing product variants (Baldwin & Clark, 2000). This leads to the hypotheses that the new model should work in dissimilar ways for new products and for incremental ones, thus interfering with product architecture decisions. Moreover, according to Whitney (2004) when a product is divided into parts and each part can be treated separately and integrated later, a reduction in complexity can be achieved.

3. *Pilot case study*

The aim of this section is to test the new model based on a pilot case study performed with novice engineers taking an MSc in Mechanical Engineering (5 years) in the course on Product Development and Entrepreneurship (fifth year option module). The researcher chose to study novices instead of experts for two main reasons: first, because they still have not crystallized their reasoning and are more open to different ways of thinking and new methodologies (Cayirdag, 2020; Horn & Cattell, 1967) and secondly it was much easier to control the novices within an academic environment than controlling experts in industry or other real-world situation. The novices are bachelor (BSc) engineers integrated in the Mechanical Engineering master program. The novices have PT nationality (13 males and 2 females) and their ages between 22 and 29 years old. The experiment took place within the Product Development and Entrepreneurship module (PDE). To test the model, a controlled environment (classes and training) was established with design teams and a training program was idealized. The idea is to give a group of teams the same design problem to which they will have to come up with a solution. Some teams will be trained in the framework proposed, and other teams will not. The result would be to check if the training in the present model would lead to a better final design (i.e., prototype), or to a set of globally better tentative solutions, compared with the other teams not trained in the model. One of the difficulties here is how to evaluate a better output. To do that a jury, composed by three individuals (two PhD professors responsible for the DPE course and one MSc engineer, all in the domain of mechanical engineering, and PD), is intended to judge the final products of the problem given on a 1–10 scale (Dorst & Cross, 2001) based on creativity and total judgment for correlating results. According to the former authors, creativity is judged by judges' own definition as already suggested. The total judgment can be evaluated by e.g., four more items referred by Dorst and Cross:

- Technical aspects: the extent to which the product meets necessary technical requirements (e.g., construction, product architecture, engineering issues, etc.);
- Ergonomics: the relation/interface between humans and the machine (product)
- Business aspects: the business and business model for the concept
- Esthetics: our affective domain response to an object or phenomenon, given by sensory or sensory-emotional values, seen as judgments of sentiment and taste.

The framing of the course is based on some knowledge gaps that novice engineers used to experience in their first job, specially a weak holistic view of engineering problems. The main objective of the course is to give the students a structure and generic methodology that allows them to translate customer needs into winning products. Furthermore, the planning of the course follows roughly the overall structure of Ulrich and Eppinger's book with some reinforcement for the entrepreneurial and business aspects. This same structure can be found in similar courses at other universities.

The module's 'project' was integrated in the global theme: 'Natural orange juice in a family environment.' The project consists of several assignments throughout the semester: 1) mission statement; 2) customer needs; 3) product specifications; 4) concept generation and selection; 5) industrial design and product architecture; 6) business plan and financial plan draft; 7) final prototype and 8) patenting (optional). The course project is to be done in groups of two to five students. The students could form groups on their own. Five groups were formed according to Table 2. The groups were then divided so that a set of groups was taken as the control with no special training apart from the normal classes of the course. The other groups – treatment group – were trained in the new model. The training consisted of a seminar in which the novices were presented with all the aspects that have been introduced earlier in this paper regarding the new model, with worked examples of application. The study was conducted over a full semester.

An empirical study based on the examining of all the groups, including a procedure to measure the creativity and the overall quality of the resulting products was performed. The final assignment of the course was used for the validation of the new model's applicability (final prototype). The prototype was evaluated by the judges. For this purpose, a protocol based on judgment of the final

Table 2. Module groups.

Group	Team	Nº group members	Received additional training?	Gender
Treatment	1	3	Yes	3 M
	2	3	Yes	2 M + 1 F
Control	3	2	No	2 M
	4	2	No	2 M
	5	5	No	4 M + 1 F

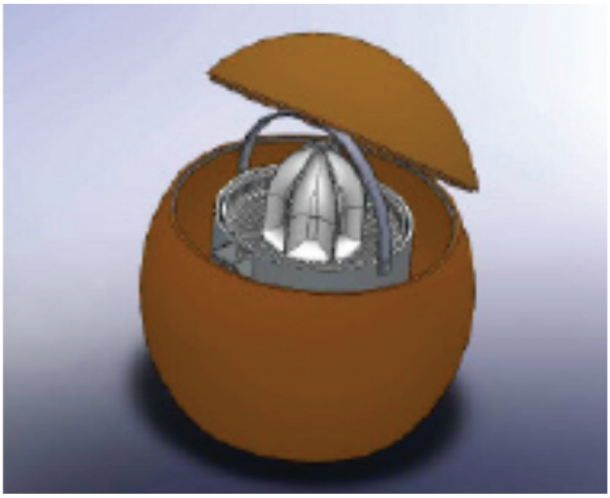

Figure 4. Orange squeezer with refrigeration final concept presented by Group 1.

product was established. The final concepts and prototypes of each group are presented in Figure 4, Figure 5, Figure 6, Figure 7 and Figure 8.

Figure 5. Domestic device to make orange juice final concept presented by Group 2.

4. Results and Discussion

To evaluate the final concepts the authors adopted the view that creativity can only be conceived as a relative concept. When applied to education, this is, the case of novice engineers under study, the

Figure 6. Production of orange juice by children final concept presented by Group 3.

Figure 7. Orange juice production solution final concept presented by Group 4.

view that within a domain there are different levels of creativity has to be adopted. This assumption can only be confirmed by showing that even the products of novice designers can be assessed reliably. In this case, observers (judges) who are familiar with the domain of PD will agree independently which concepts are creative or not, and classify them in a proposed scale. The level of agreement will be an indication for the reliability with which creativity can be measured by the 'consensual assessment technique' proposed by Amabile (1982). The technique developed by Amabile (1982) allows for the assessment of the creativity of products and as a refinement of previous subjective methods. The creativity assessment technique is grounded in the following consensual definition of creativity (Amabile, 1982, p. 1001):

> A product or response is creative to the extent that appropriate observers independently agree it is creative. Appropriate observers are those familiar with the domain in which the product was created or the response articulated. Thus, creativity can be regarded as the quality of products or responses judged to be creative by appropriate observers, and it can also be regarded as the process by which something so judged is produced.

Studies testing the methodology in schools and undergraduates, in both artistic and verbal domains were performed by Amabile (1982). Judges, who are considered to be experts in the domain under study, were instructed to use their own subjective definition of creativity as they rated collages and poems, relative to one another rather than against some standard (Amabile, 1982). In this case, the agreement between judges is measured by the alpha coefficient, represented in equation (1) given by the Cronbach's coefficient (Cronbach, 1951):

Figure 8. Equipment to make orange juice final concept presented by Group 5.

$$\alpha = \frac{K}{K-1}\left(1 - \frac{\sum_{i=1}^{K}\sigma_{Y_i}^2}{\sigma_X^2}\right) \tag{1}$$

where K is the number of components,$\sigma_X^2$is the variance of the observed total test scores for the current sample of persons, and $\sigma_{Y_i}^2$is the variance of component i for the current sample of persons. The judges were composed by three individuals (as stated before). Each judge rated all the five concepts individually. The inter-rater reliability was determined by computing the alpha coefficient for the agreement between the judges. The alpha coefficient for creativity was computed in 0.807, hence a good reliability. An overview of the scores (judges, mean and standard deviation for creativity, and mean and standard deviation for total judgment) given for each concept elaborated by the 5 groups is shown respectively in Table 3. Creativity was also correlated to total judgment (Table 4).

Table 3. Scores, mean and standard deviation (in brakets) of the three judges (1–10 scale).

Group	Concept	Judge 1	Judge 2	Judge 3	Creativity	Judge 1	Judge 2	Judge 3	Total judgment
Treatment	G1	9	8	8	8.3(0.6)	8	8	8	8.0(0.0)
	G2	9	8	8	8.3(0.6)	9	8	8	8.3(0.6)
Control	G3	8	5	9	7.3(2.1)	8	5	5	6.0(1.7)
	G4	9	5	7	7.0(2.0)	9	5	5	6.3(2.3)
	G5	8	7	8	7.7(0.6)	8	7	8	7.7(0.6)

Table 4. Correlation value.

	Creativity
Correlation with total judgment	0.906

The products from groups 1 and 2 stand out as the best ones in creativity and also in total judgment. As so, the groups that were trained with the model achieved better results in terms of creativity and total judgment (groups 1 and 2) than the groups that were not trained with the model (the control set groups).

Nevertheless, due to the score for the standard deviation for creativity presented by both groups (all the 5 teams) it was necessary to search for statistical significance of data. The first step was to verify if the data from the Treatment and Control group were both normally distributed. Using R (https://www.r-project.org/) for computing 'Shapiro-Wilk normality test', the Treatment group ($W = 0.639$, p-value $= 0.001 < .05$) rejects the null hypothesis that data are normally distributed. For the Control group ($W = 0.864$, p-value $= 0.107 > .05$) the null hypothesis is not rejected. As so, data has to be evaluated by a non-parametric test (e.g., Montgomery & Runger, 2003) such as the 'Mann-Whitney-Wilcoxon' test that compares the probability to get higher value from one group with the probability to get higher value from another group. As the computed p-value turns out to be 0.186, a value higher than .05 significance level, the null hypothesis is accepted, i.e., the randomly selected value of Treatment's population (Mean = 8.333, SD = 0.516) is considered to be equal to the randomly selected value of Control's population (Mean = 7.333, SD = 1.500). In other words, the difference between both groups' population is not big enough to be statistically significant. This means that it is still not possible to claim whether the brief teaching of the new framework affects the ability of the designers to produce more creative designs/prototypes, and further experiments are required to strengthen these preliminary results.

5. Conclusions

The general objective of this article was to establish a model for fostering creativity based on the understanding of how creative ideas are generated and how they can be brought to the PDP. In order to address that objective and answering to the research question queried, a model containing an inspiration domain, two main processes of design, based on the concept of idea-space, heuristics and process loops has been described and tested with novices. The conclusion is that groups with formal training in a design method (the new model) outperformed others group, thus allowing to believe that the model can be a framework that fosters higher creativity rates in an academic PDP. Of course, difficulties in building a successful controlled environment can limit the study, such as the case of random groups' formation and the absence of a formal descriptive study, or the recognition that the number of samples (groups) and judges' scores was too small. In any circumstances, the standard can be further used for both describing and prescribing the process of creativity for PD outputs, as Blessing and Chakrabarti (2009) focus on both types for a successful design research methodology.

To that extent, during the classes, the novices were observed and performed activities such as: looking for inspiration to the new orange squeezer in the internet, performing questionnaires to fulfill customer needs, asking the opinion of experts on the subject, and searching for technological research literature in the field, among other activities in a normal PDP. They have also developed customer needs, made observations, and performed brainstorming sessions. Moreover, all the groups have reached a new solution, composed by functions and components, and set a final product architecture, thus building their own extended idea-space as other studies demonstrated (Marques et al. 2014, Marques 2016).

Furthermore, the findings show a possible path for further developments in understanding more deeply creativity in design/PDP, helping students in understanding what factors typically affect the promotion of creative activities and important PD outputs, such as the awareness of the inherent iterative nature of the design and creative process, as typical PD or design models present the process as a linear step-by-step sequence of tasks. Further studies, with more students will most probably provide more significance to the model. Regarding that aspect, there is also a need to clarify the ideal and quick choice to be made between the specialization and generalization loops in the testing phase. Since experts and novices have distinguished ways for decision-making, this aspect outlooks replications using experts in working environments. The problem here is to clearly identify what is a paradigm shift or not, which is sometimes difficult to be distinguished especially when an analogy is made to incremental and radical innovation.

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